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Integrating Allowable Design Strains in Composites with Whole Life Value

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Abstract

Fibre-Reinforced Plastics (FRPs) have been used in civil aerospace vehicles for decades. The current state-of-the-art in airframe design and manufacture results in approximately half the airframe mass attributable to FRP materials. The continual increase in the use of FRP materials over metallic alloys is attributable to the material's superior specific strength and stiffness, fatigue performance and corrosion resistance. However, the full potential of these materials has yet to be exploited as analysis methods to predict physical failure with equal accuracy and robustness are not yet available. The result is a conservative approach to design, but one that can bring benefit via increased inspection intervals and reduced cost over the vehicle life. The challenge is that the methods used in practice are based on empirical tests and real relationships and drivers are difficult to see in this complex process and so the trade-off decision is challenging and uncertain. The aim of this feasibility study was to scope a viable process which could help develop some rules and relationships based on the fundamental mechanics of composite material and the economics of production and operation, which would enhance understanding of the role and impact of design allowables across the life of a composite structure.

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Keywords: Composites, Impact, Damage, Whole Life, Surplus Value, Value Driven Design.

1. Introduction

The full exploitation of FRP materials for structural applications remains a challenge because the analysis methods which are required to predict key physical failure modes with equal accuracy and robustness are not yet available. For example a key limiting factor on high-strain and buckling/post-buckling composite designs is that today's standard analysis tools are not capable of accurately and robustly representing the damage mechanisms which ultimately lead to structural collapse. Moreover, the manufacturing process linked with configuration design also influences both the allowable stresses and the mode of failure. Thus current designs are constrained from exploiting the full potential of available materials due to the limits of current analysis methods and fundamental knowledge on the sensitivities and boundaries of behaviors expected through an airframes whole life.

Today's aircraft primary structure is designed to function at relatively low strain levels as part of a 'no-growth' of damage philosophy in design due to technology limits in the fields of damage mechanics modelling, in-service damage detection and repair [1-5]. The resulting designs do not produce the full weight saving potential of the composite materials, but do offer significant advances in terms of through-life inspection and maintenance intervals. Examining the through-life value of such structures demonstrates the significant value of the resultant in-service characteristics to the aircraft operators [6]. As modelling, detection and repair technology develops the potential to introduce aircraft composite structures which work at high-strain levels and that allow and manage the growth of damage will ultimately arise. However, fundamental knowledge on the interaction between design philosophy, such as maximum working strain, and resulting structural weight and the impact on in-service inspection and maintenance requirements are currently not

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available. Without such knowledge no models or physics based mathematical function can be derived to allow aircraft designers to trade-off these design characteristics. The issue is compounded further by the variations and flaws that are introduced by the manufacturing process. The additional uncertainty can result in further conservatism. It may be the case that a more rigorous manufacturing process control and stricter quality system may improve through-life costs, perhaps at the cost of a higher scrap rate at manufacture. This complex dance between embedded manufacturing flaws, in-service damage, maintenance and repair ultimately requires a detailed level of understanding of the materials, processes and performance, including costs. Thus, when designing a structure the design philosophy must be set before it is possible to optimise the structural configuration and material combinations, and such an approach will not ensure the best design philosophy is selected for an optimum whole-life solution.

1.1. Aims & Objectives

The aim of this work is to understand and characterise the influence of damage design philosophy on the through-life value of composite aircraft structures. More particularly to create and harness new science and engineering knowledge on the impact of maximum working strain on both the structural weight and through-life inspection and maintenance intervals of large unitised aerospace structural components. In order that a clear route for immediate and significant impact from this research is available, the discipline specific fundamental knowledge created will be integrated together through a whole-life value modelling approach. This will thus harness the new knowledge to create new OEM and operator financial understanding of the value balance between lighter aircraft structures and greater through-life inspection and maintenance burdens. Such knowledge will help direct material, design and inspection technology research, with the combined objective that the next generation of aircraft composite structures will maximise the value for all whole-life stakeholders.

2. Obtaining Design Allowables

The relationships between the many geometric and material variables in composite materials are complex and the process of identifying a simple relationship to mark failure is not straightforward. To that end, procedures have been established to allow a conservative estimate of the acceptable design stress and strain. This is driven by the uncertainty in behavior when unseen flaws are present in the structure. In the case of composites the probability of an impact in service causing unseen damage is almost certain, so the acceptable design stress must be based on the strength of the material with such damage. Hence the dominant tests are based on specimens tested in tension and compression after impact (TAI, CAI), or open hole compression, which tend to show the most conservative position [7-9].

There are a number of ways of approaching this, but perhaps the most common is to plot the allowable strain for a given AML. AML is the “Angle Minus Longitudinal”. AML is simply the difference in percentage of the angled plies to the 0° plies. For example a layup with 40% of the stack at ±45° and 30% at 0° has an AML of 10. The AML is a simple reference to indicate whether a layup is dominated by off angle plies or not.

Fig. 1 below illustrates a very simplified version of the process in the case of TAI and CAI specimens. The first step is to impact a coupon specimen. The impact is effected at a set energy which as estimated from potential in-service impacts, for example a dropped tool or severe hail. There are several variations here, but all focus on the energy needed to produce inspectable damage. The damage detectable is called BVID (Barely Visible Impact Damage). The depth and extent of this is selected based on that which gives a 90% probability of detection using normal visual inspection. An interesting aspect of this is the relaxation phenomenon, whereby environmental conditions such as moisture absorption, cause a reduction in the indentation. Thus in-service conditions are directly linked to the definition of impact flaw sizes and hence final damage allowables. The damaged specimen is then tested to failure in compression, tension or shear. The failure strain is noted for this AML.

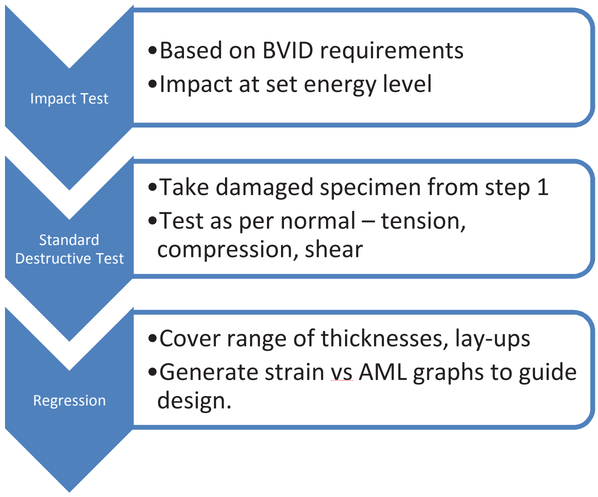

Fig. 1: Outline process for failure strain versus AML.

The real industrial process is of course more complex, with a test pyramid from coupons and structural details up to full scale demonstrators.

Of course, in practice since many layups can be represented by a single AML, tests must be carried out on all as the stacking sequence will influence the results. And since edge effects and other complexities with the environment also come into play, the tests must include open hole tension, open hole compression, and hot wet conditions. Naturally this is a lot of testing, typically +3000 specimens for a single material system and processing route, and the resulting curves have a significant degree of scatter. It is clear that with a conservative approach, the worst case will drive the acceptable design strains down.

The result of this effort is a series of curves that can be used by designers to compare working stress levels to the allowable strains obtained. It is a pragmatic solution to a very complex problem.

However, a number of immediate questions arise from this. The impact damage from the test is dependent on the boundary conditions and the layup, and the curves obtained are strictly limited to the range of thicknesses, layups and boundary conditions used. Therefore designers are reluctant to risk choosing material configurations outside these ranges, or they may need to commit significant resources to reducing these risks via extensive test programmes. Since the relationships are completely empirical it is difficult for a designer to make choices even within this range. Designing this way is cumbersome. Although the process for obtaining the allowable strains is centered around damage, it is not linked to typical inspection intervals and processes, hence the through life value of a material change decision is also unknown. The issue is further clouded when trying to account for manufacturing processes and costing in composites, which is difficult [10-12]. However, this is true for the design of metal structures also, for example with respect to the introduction of advanced joining technologies such as friction stir welding [13,14]. To consider how such changes can be accounted for requires a different approach.

3. Value Driven Design

Value Driven Design [15] is an approach which takes a wider view of the design process, attempting to move away from a strict, requirement based approach and to apply unconstrained optimization to the whole system, considering its value over the whole life. It therefore eschews the typical goal of many design optimization studies to minimize weight or cost, preferring to try to optimize for system value, which includes revenues, taxes and any other stakeholder element [16-18].

Surplus Value has emerged from some studies as a good objective function which encompasses the needs of the relevant stakeholders in the design of an aircraft or similar complex system [19]. This of course includes both the manufacturer and the operator, and the form used here brings manufacturing cost and operating costs into the one overall evaluation criterion, providing an opportunity to link otherwise separate parts of the life cycle.

Surplus value is a term originally popularised by Marx who used the concept in his political economic theory, to show that the excess value of workers effort was the opportunity for profit. Economic theory has discussed and developed the concept significantly[20]. It has also refined its definition to become a useful concept in understanding the economic output of any enterprise.

The accepted definition of surplus value (V_S) as a starting point for this work is:

$$V_s = P_R - C_{man}$$

That is the reservation price (P_R) minus all the costs incurred (C_{man}). Reservation price is defined as the price paid by the customer for the product that makes the net present value of the transaction to be zero. In other words, the reservation price is the maximum possible price that a customer will pay before the cost of ownership and operation will result in losses. By expanding on each of these terms, more specific variants of the equation can be used which have direct relevance to a given product or system. There are several variants of this equation which have been presented in aviation literature. For example, Curran et al [21] use a variant re-expressed to focus on profit:

$$V_s = \sum (R - C_{doc})(1 + r)^i - C_{man}$$

In this case, R is the revenue from operations, C_{doc} is the standard direct operating cost, r is the discount factor, i the life of the programme, and C_{man} the manufacturing costs. But this remains very high level and for it to be of use to the engineering functions, it is necessary to reformulate it so that it expresses the key elements which are meaningful to the aircraft designer. For this work, the variant of the surplus value equation developed by Collopy[11] is used. In this very useful version all of the potential revenues and costs are expressed separately.

In this case it is defined as:

$$V_s = r_p N_{a/c} \{ r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M \} - C_D$$

Where:

r_p and r_c – These terms refer to multipliers on a single year's revenue and costs based on the discount rate and program life for the manufacturers and customer (operator) respectively.
$N_{a/c}$ – The number of aircraft produced, including test and production standard aircraft.
F_y - Flights per year
$R_{P\&C}$ - Revenue generated from passengers and cargo
C_{OP} - Operating Costs, includes both the direct and indirect operating costs.
$C_{D\&C}$ - Delay and Cancellation Costs
C_E - Externality Tax, environmental taxes for noise, emissions and other societal good.
C_M - Manufacturing Costs
C_D - Developmental Costs

The key characteristic of this approach is a mathematical formulation over the product whole life, which accounts for the total size of the product programme, and including revenues, maintenance, and outages. Price et al [6] examined the sensitivities of surplus value to key cost and engineering parameters calculating, for example maintenance to manufacturing sensitivities, fuel to maintenance sensitivities etc. These values provide mathematical mechanisms which directly link critical elements of the system which have diverse physics, units of measurement and time domains.

$$\text{Value Influence of Manufacturing to Fuel} = \frac{\dfrac{\delta V}{\delta C_{Fuel}}}{\dfrac{\delta V_S}{\delta C_M}} = \frac{\delta C_M}{\delta C_{Fuel}}$$

These were termed Value Influence Coefficients, and through their study Price et al [6] demonstrated the relative changes in value with weight and maintenance costs over the life of a fleet. For the examined case study, the Value Influence of Maintenance was such that maintenance savings could potentially offset increases in vehicle weight.

Fig. 2 shows a typical surplus value versus programme lifetime chart. Reducing vehicle weight or increasing maintenance intervals will tend to increase programme value. However, assuming both vehicle weight and maintenance intervals will be negatively linked to material allowables (i.e. increasing material allowables by reducing conservatism will decrease vehicle weight but increase the requirements for scheduled maintenance) there will necessarily be a need to perform a systems level trade-off to maximise the potential value of a programme.

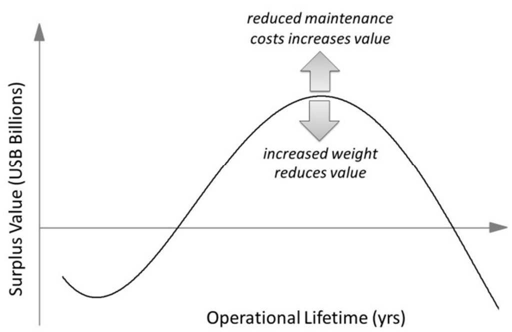

Fig. 2: Surplus Value over time – showing how factors can influence value.

Surplus Value therefore offers a mechanism whereby the choice of material allowable and coupled maintenance intervals can be assessed against the whole life of the product.

4. Progress

The previous two sections briefly outlined the main elements of obtaining allowable strains for a material and the potential of the value driven design approach to help understand the potential benefit of reducing some of the conservatism and uncertainty in material failure behaviour.

It is clear that the complete integration of such complex models is a major challenge, and with high risk in that there is no certainty that meaningful guidelines will emerge from such an integrated approach.

The feasibility study therefore intended to investigate the methods in more detail and to set the scope of a larger project to attempt to develop a deeper and more general understanding of the mechanisms and relationships. Therefore the intention was to identify the rules and procedures used, and to see if a linkage was possible to allow the development of new direct relationships and improved understanding.

4.1. Tasks & procedures

To provide a foundation for scoping out a research proposal the work focused on formulating a model which would allow variation in geometry and material properties, in predicting damage in carbon fibre reinforced materials using standard models available in commercial finite element packages.

Initial Modelling

A model was constructed in ABAQUS and validated against a series of experimental tests undertaken in a parallel project. The model reflected the material used and had a high fidelity representation of the actual test conditions. Faithful representation is key in such models where sensitivity to various conditions can change results significantly.

Validation

Validation was carried out in terms of load and observed failure bases and also against scans of the damaged specimens before and after impact. Both area and depth of damage were recorded and compared.

Automation for Aspect Ratio Study

Having obtained a degree of confidence through the validation of the model the next key element was to automate the process - wrapping around a controlling application which would allow multiple future studies. A python script was written to reproduce model conditions and to allow variations in the material lay-up and in basic specimen geometry. The main aim here was to investigate how complex the model of the plate was and to determine if it could be automated over the range of properties which would require examination during a full research programme. In particular, this covered the inclusion of time based degradation models, residual stresses, elastic boundary conditions and large numbers of non-standard lay-ups from quasi-isotropic to fully orthotropic. Fig. 3 below shows the resulting damage plots for plates of aspect ratio 1, 2 & 3.

Obtaining the Allowable Strain

At this point a simple estimate based on the flaw size was used to obtain the reduction in residual strength with the relative flaw size obtained from the simulation. Of course, in practice this is much too simplistic, but it is sufficient to allow the framework to operate.

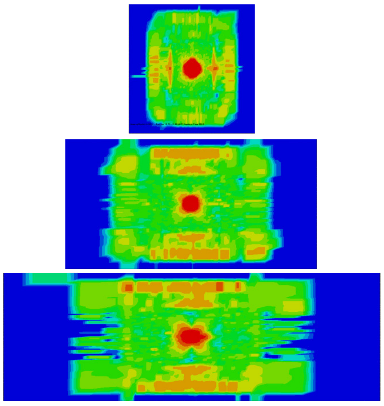

Fig. 3: aspect ratios of 1:1, 2:1 and 3:1 under the impact loading.

Assessment of Effects in Surplus Value

The initial investigation into the inclusion of flaw sizes and working stresses identified this to be a complex problem. Although it was possible to use some simple rules from damage tolerance guidelines which can give an indication of maintenance intervals in number of cycles based on the detectable flaw size. A pro-rata increase in the intervals was used in the surplus value maintenance model to estimate the relative change caused. In addition the increase in thickness was multiplied in proportion to provide an estimate of the change in structural weight. Thus, an estimate of surplus value now accounts for the change in weight and the change in maintenance intervals.

Lessons Learned

A number of key challenges emerged from the study which should form the basis of useful research work:

1. The estimation of allowable strains for composite materials is a complex process which has a number of limitations, the major one of which is the empirical nature and lack of rigorous procedures to allow understanding of real physical relationships and drivers.
2. There is a strong linkage between the acceptable stresses in the material and the whole life value of the system. However the exact nature of the relationship is buried in a complex set of rules and uncertainty.
3. The problem is compounded by the need for a very large number of tests. Even simulation based approaches will need a large number of combinations to be of use. Automation and the use of statistical and meta models will be essential to help explore the problem.
4. The understanding of this problem is at the core of many decisions and has a major effect on the size and cost of composite structures.
5. There is both a fundamental problem to be solved and the potential for real application benefits - if successful and physics based linkages can be formed then step change in understanding will be created and step change in application performance enabled.

Below the proposed next main steps for a full project are outlined:

Scope: Define through a series of industrial partner workshops a focused family of structural elements and detail design features from incumbent aircraft composite structures, which represent the critical design challenges for the OEMs, and inspection and maintenance challenges for the operators. A key deliverable will be mapping of the critical performance of these elements and detail design features, from their lowest level design and material parameters to their relation to vehicle whole-life performance.

Coupon level: For a focused family of materials coupled experimental and modelling research will aim to characterise the dependence of damage propagation on maximum working strain. Here advanced damage mechanics modelling and validating experimental data will be required, extending the current state-of-the-art on composite damage propagation. A key deliverable will be validated FE damage mechanics models appropriate for the materials and damage types identified by the industrial partners. Parameterised versions of these models will be used to generate material level relationships between material structure, damage form, maximum working strain and damage growth rate.

Structural level: Via a series of systematic experimental and computational studies using the validated FE damage mechanics models the influence of structural features on the impact of damage propagation and working strain will be further expanded. Here new design rules and guidelines will be formulated for structures with greater maximum working strains. A key deliverable will be the knowledge, data and design models or physics based mathematical functions to enable initial sizing of structural details within high-strain composite components. This output will advance the current understanding of composite damage propagation and damage tolerance composite structures.

Component Level: Integrate the new design rules and data into today's industrial design tools for large aerospace unitised components, and use these to design a series of virtual and physical demonstrator components with varying combinations of weight and inspection interval targets (referenced to today's aircraft entering service). Design of Experiments (DOE) and regression analysis of the virtual demonstrators will enable the formulation of higher level design rules and formulas. Experimental verification of the structural and inspection performance of the physical demonstrators will allow design rule and formula calibration. Moreover the demonstrator components produced in this work package will also be used for impact activities, raising awareness of the technology for industrial decision makers and speeding the future adoption of the technology in industry.

Vehicle Level: Guiding the above demonstrator activity will be the overarching requirement to harness the developed science and engineering knowledge in order to model and understand the evolution of component whole-life value. The structural weight of the demonstrator components will be derived from the resulting sizing and this used to model the impact on aircraft payload and fuel burn. Industrially calibrated activity based cost modelling and digital manufacturing methods will be used to estimate manufacturing costs, and digital manufacturing and discrete event simulation will be used to estimate in-service inspection and maintenance costs. Ultimately the impact of maximum working strain on the balance of OEM and operator value will be visible and interrogable.

5. Conclusions

The study looked in some detail at a challenging problem in composite structures, namely the estimation of allowable design strains and the impact of this on the whole life value of the vehicle. The problem was outlined and the scope of a full study developed. The initial results did identify that linkages were possible and that understanding of the structural performance and corresponding value was possible. Advanced modeling methods, automation and statistical models, supplement with a strong test programme for validation, will be needed to develop the new knowledge.

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